

# OPTICAL EMISSION CHARACTERISTICS OF HELIUM BREAKDOWN AT PARTIAL VACUUM FOR POINT TO PLANE GEOMETRY\*

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## Abstract

In general, power devices and systems operating in vacuum or space environment are more susceptible to partial discharges, corona, or volume discharge due to the partial vacuum conditions. Partial discharge and breakdown measurements have been performed on electrical equipment operating in such environments for over decades. In spite of all the studies, fundamental understanding of partial discharge or corona initiation has not been understood completely. Various means of detection have been used over the years, including the detection of electromagnetic emissions using antennas or by observing the current through the ground cables to obtain a better understanding. The measurements are usually analyzed together with other techniques like visual inspection, transient voltage/current measurements and acoustic/optical characteristics.

In this paper we present our work on optical emission characteristics of breakdown events at partial vacuum for point-to-plane electrode configuration, operating at dc and 20 kHz frequency in helium. A dc-offset-ac voltage source for the high frequency experiments and a pure dc power supply for dc breakdown experiments were used. Preliminary data of voltage and current waveforms along with the light emission data are presented. The optical signal detection of this set-up includes a photo-multiplier-tube and a digital pico-ammeter. Optical data collected by a PMT (Photo Multiplier Tube) as a function of time is presented. Presence of optical emission was also recorded by a video camera and frame-by-frame images were used for data analysis.

## I. INTRODUCTION

The next generation space vehicles are likely to utilize higher voltages than the traditional 28 Vdc for onboard power distribution. Such is already the case for the International Space Station (ISS), which utilizes 120 Vdc. The availability of switching power supplies operating at high switching frequencies makes it important to consider the effects of these higher operating frequencies with respect to corona and gas breakdown in space

applications. Such phenomena within power system components are considered unacceptable in systems where long lifetime and reliability is necessary [4].

The literature suggests that the dielectric strength of certain gases falls off drastically at frequencies of 10s of kHz, which is not theoretically predictable [1]. Although there have been studies on the influence of voltage signal frequency on gas breakdown over specific frequency range, this behavior over the range below 1 MHz is not completely understood. In addition, existing data cannot be extrapolated for miniature systems with smaller electrode gaps operating at very low pressures. Our recent studies confirm that high frequency operation in space could be a major concern when designing space power systems [2], and that the breakdown voltage levels at high frequencies (< 1 MHz) can indeed be lower than the dc breakdown voltage levels, at certain pressures.

Partial discharges are detrimental to a power system as they are constant sources of power loss and electrical noise (EMI). Furthermore, they can be a major problem at the component level, causing solid insulation deterioration and eventual breakdown. With the development of the next generation space and aerospace vehicles using higher voltages than traditional 28 V dc power, the need for data to design high voltage space power systems is more desirable. Currently, there are several initiatives within the government agencies (such as NASA and Air Force), planning to use 270-volt distribution power [4]. Some sub-systems also use high frequency (in the 10s of kHz) voltages, for switched mode power conversion. In general, the corona or partial discharge initiation voltage is a function of several design and environmental parameters. The most important factors to be noted are the operation pressure, the electrode gap/geometry, and the frequency and voltage level of the applied power within a power system [6]. Commercial dc to dc voltage converters typically operate with intermediate frequencies in the range of 20 to 100 kHz. These voltages and frequencies are considered problem areas for corona and breakdown concerns in flight vehicles subjected to low pressure environments [5].

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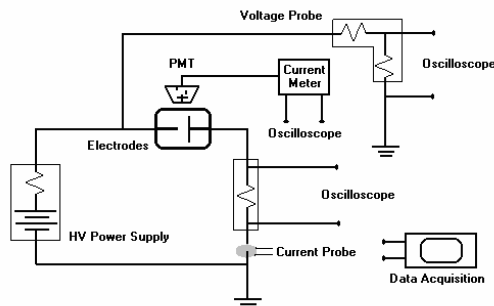
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14. ABSTRACT <b>In general, power devices and systems operating in vacuum or space environment are more susceptible to partial discharges, corona, or volume discharge due to the partial vacuum conditions. Partial discharge and breakdown measurements have been performed on electrical equipment operating in such environments for over decades. In spite of all the studies, fundamental understanding of partial discharge or corona initiation has not been understood completely. Various means of detection have been used over the years, including the detection of electromagnetic emissions using antennas or by observing the current through the ground cables to obtain a better understanding. The measurements are usually analyzed together with other techniques like visual inspection, transient voltage/current measurements and acoustic/optical characteristics. In this paper we present our work on optical emission characteristics of breakdown events at partial vacuum for point-to-plane electrode configuration, operating at dc and 20 kHz frequency in helium. A dc-offset-ac voltage source for the high frequency experiments and a pure dc power supply for dc breakdown experiments were used. Preliminary data of voltage and current waveforms along with the light emission data are presented. The optical signal detection of this set-up includes a photo-multiplier tube and a digital pico-ammeter. Optical data collected by a PMT (Photo Multiplier Tube) as a function of time is presented. Presence of optical emission was also recorded by a video camera and frame-by-frame images were used for data analysis.</b>		
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This paper summarizes our current work by giving a brief description of the experimental setup for optical detection followed by analysis and interpretation of the optical emission data acquired. We present the optical characteristics of helium dc and ac breakdown at partial vacuum conditions for point-plane electrode geometry.

## II. EXPERIMENTAL SETUP

The experimental setup consists of a high vacuum chamber, high voltage power system and a data acquisition system. The vacuum chamber is equipped with an optical window in addition to the ports for voltage input/output, pressure gauges, and gas input. The electrode system consists of a stainless steel point electrode and a grounded copper plate. The point electrode is machined to a tip radius of approximately 0.5 mm and placed 1.0 cm above the plate electrode. The chamber is purged by first pumping out and then filling with helium gas for each experiment set. Once the purge is completed, helium is used as the operating gas. The chamber pressure is maintained constant throughout a particular set of breakdown events by controlling the gas inlet valve and the vacuum pump. The breakdown experiments were conducted as pressure is varied from 0.2 torr to 3.0 torr. The power supply used in these experiments is an in-house-built power source constructed from a dc in series with an ac source connected with a high frequency step-up transformer. The final signal generated by this setup is a dc-shifted sinusoid with no negative values. The applied voltage is gradually increased by simultaneously increasing the dc and the ac voltages, until a breakdown event is observed. At every pressure level, three successive breakdown events are recorded and these voltages are averaged to form the data point for that particular pressure. The chamber is then flushed with helium before taking the next data set to avoid any contamination. The experimental set-up including the power source and the diagnostics is shown in Figure 1.



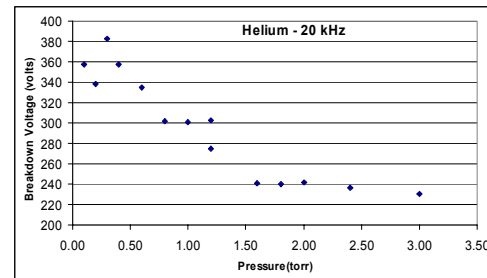
**Figure 1:** Experimental Setup.

Voltage and current waveforms, along with the light emission data from the discharges are collected. Optical data is collected by means of video camera for optical

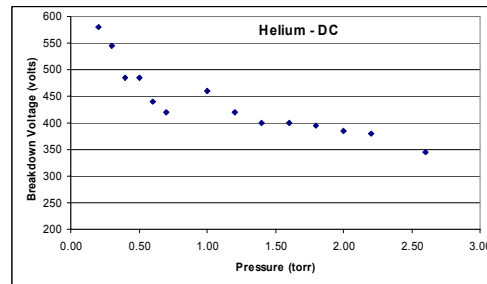
images and by PMT for time evolution of the light emission from the breakdown. The videos are then converted into frame-by-frame still images for better understanding the process step-by-step. We also conducted experiments with dc source to obtain dc breakdown data to compare it with the ac-high frequency data. The experimental procedures of the dc data were similar to those in ac breakdown experiments.

## III. EXPERIMENTAL RESULTS

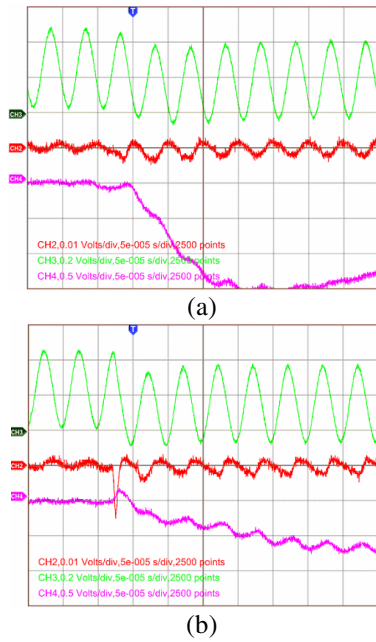
Preliminary studies on the high frequency breakdown of helium for this configuration were reported previously [5]. In this study, the breakdown voltage versus pressure for this configuration was presented, as shown here in Figure 2 [5]. These studies show that the breakdown voltage decreases as pressure increases. At around 1.50 torr, the breakdown curve seems to reach a steady minimum. DC breakdown data as a function of pressure for the same experimental conditions is shown in Figure 3 [5]. It was observed that the breakdown voltage characteristics under dc conditions also exhibit a pattern similar to the ac breakdown curve but with a higher breakdown voltage. In this case, breakdown voltage decreases as a function of pressure and reaches to a steady level around 1.5 torr pressure. As seen in Figure 2, the breakdown voltage characteristic for ac exhibits a pattern similar to the typical Paschen curve for dc breakdown in gases. Further data above 3 torr is needed for better comparison.



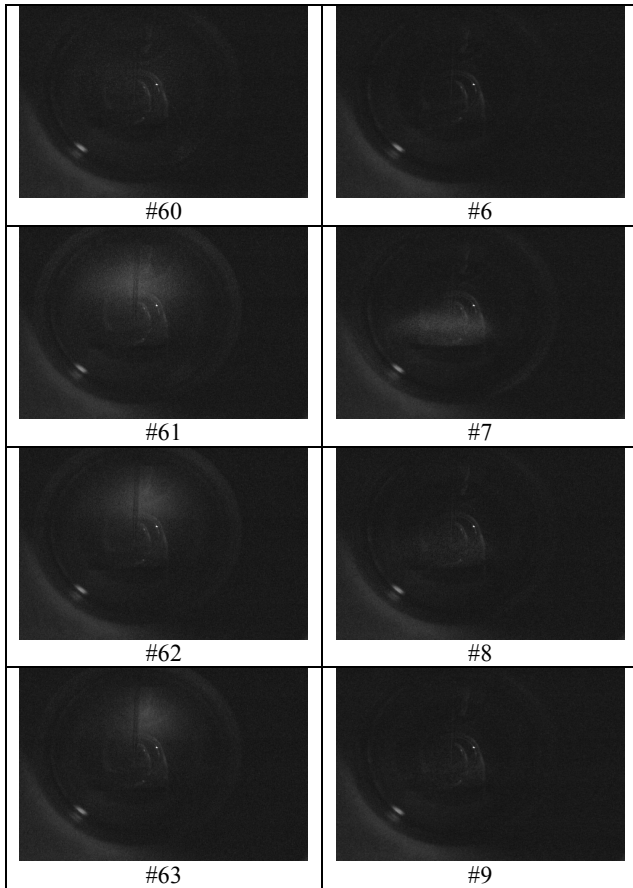
**Figure 2.** Breakdown voltage as a function of pressure for point-to-plane electrode configuration with 1-cm gap distance for 20 kHz signal [5].



**Figure 3.** Breakdown voltage as a function of pressure for point-to-plane electrode configuration with 1-cm gap distance under DC voltage.

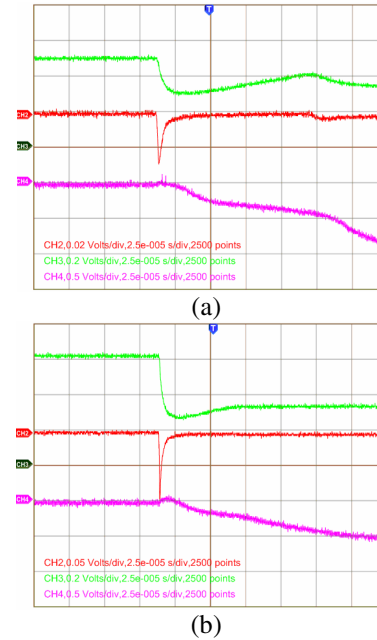


**Figure 4.** Voltage (top), current (middle) and optical emission (bottom) waveforms for a breakdown event at (a) 0.4 torr and (b) 1.8 torr at 20 kHz applied voltage.



**Figure 5.** Optical video images of the 20 kHz breakdown event shown frame-by-frame, at: 0.4 torr (left) and 1.8 torr (right). The video images are recorded with 30

frames/sec, corresponding to about 33 milli sec between each consecutive frame.



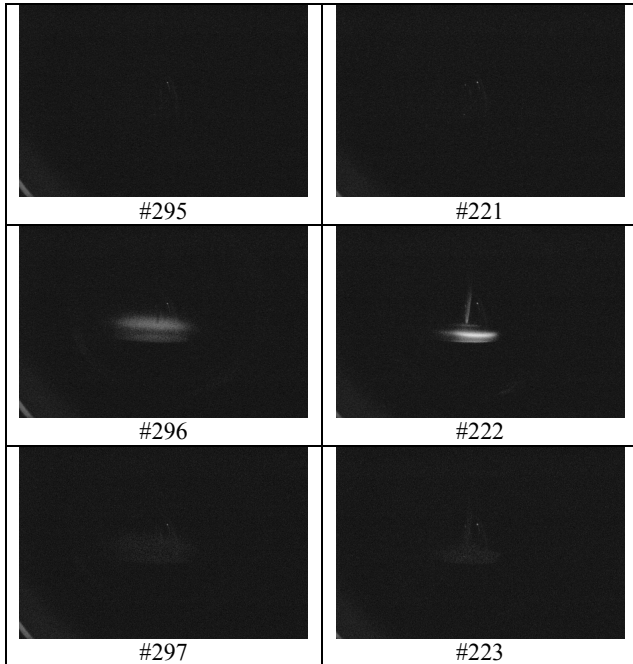
**Figure 6.** Voltage (top), current (middle) and optical emission (bottom) waveforms for a dc breakdown event at (a) 0.4 torr and (b) 1.8.

A representative voltage, current and the PMT waveforms as a function of time for the ac breakdown events are shown in Figure 4 at two different pressures. The frame-by-frame images obtained by the video camera for the same experimental conditions are shown in Figure 5. The voltage and current waveforms suggest that the breakdown is a relatively short event occurring within a few microseconds. Once the breakdown is initiated, a voltage collapse and a transient current are recorded. The light emission from the electrode gap is observed for several cycles, although the voltage and current waveforms indicate this process to be in the microsecond range (Figure 4). Similar voltage, current and optical emission waveforms for dc breakdown events are shown in Figure 6 for (a) 0.4 torr and (b) 1.8 torr. The corresponding optical image data recorded by the video camera is shown in Figure 7 for these breakdown experiments.

## IV. DISCUSSION

Earlier studies by Pfeiffer [3] for air gaps on partial discharge inception show that the breakdown voltage of inhomogeneous field gaps decreases significantly with the increasing frequency. It was also observed that the breakdown voltage falls down to as much as 50% of its value at 50 Hz if the operating frequencies are taken in 10s of kHz range. The data recorded in our laboratory support that the breakdown voltages at higher frequencies are lower than the dc breakdown voltages. The data by

Pfeiffer [3] was obtained for atmospheric pressures whereas our data is for partial vacuum conditions, thus a one-to-one comparison could not be made.



**Figure 7.** Optical video images of the dc breakdown event shown frame-by-frame, at different pressures: 0.4 torr (left) and 1.8 torr (right).

In general, a low intensity glow discharge is observed around both the electrodes, but mainly seen at the cathode region (plate electrode) at higher pressure, and at the anode region (point electrode) at lower pressures. Visual inspection of the acquired images suggests that the breakdown has a lower intensity at lower pressures compared to the optical emission at higher pressures; however, this is not the case. The glow is relatively diffused at lower pressure making it appear to have a lower intensity. Optical emission waveforms recorded by PMT show that there is higher emission rate at lower pressures compared to more confined glow with lower optical intensity at higher pressure.

As seen in the voltage waveforms of Figure 4, most of the breakdown events occur at the falling edge of the ac signal. Once the discharge is initiated, it becomes almost self-sustaining for few milli seconds. At the breakdown, the dc offset value decreases, allowing the signal to go negative, as seen in Figure 4. Once the breakdown is initiated, the discharge current follows the applied voltage signal. During this process, the light emission steadily increases, following a similar pattern as the current. From the video images, it can be observed that the light emission continues for several milli seconds. It was further observed that the breakdown starts with a transient current and this current magnitude increases as the pressure increases (Figures 4a and 4b).

Similar observations were recorded with the dc breakdown experiments. In this case also, there is never a complete voltage collapse across the gap. However, a breakdown does occur with observable transient current and optical emission. Once the discharge is established, a constant voltage and current are observed between the gap. Similar optical emission characteristics were also observed for ac breakdown events. It was observed that the dc breakdown events were relatively faster than the ac breakdown events. The dc breakdown events were not self-sustaining in general whereas the ac breakdowns were.

## V. CONCLUSIONS

The breakdown voltage of helium operating at 20 kHz in partial vacuum, for a point-to-plane electrode configuration decreases as pressure increases, until a minimum is observed around 1.5 torr. Further experimental testing is needed to conclude if a Paschen type behavior is actually present. Transient current magnitude in both ac and dc breakdown experiments was observed to increase with gas pressure, as expected. In both the cases, breakdown initiation occurs in microsecond range. At breakdown, there is no complete voltage collapse across the gap, however, a self sustained glow discharge was observed for several milli seconds. Further analysis of the optical emission is needed to fully understand the fundamental physics of the the high frequency breakdown.

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